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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

PROCESS OF LEAD-DEPOSIT ACCUMULATIONS ON AIRCRAFT-ENGINE SPARK PLUGS

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SUMMARY

Tests with CFR and aircraft-type single-cylinder engines were made to investigate the progressive accumulation of lead deposits on spark plugs under nonvarying operating conditions. Deposit-weight determinations and photographic observations are presented, which demonstrate the following characteristics of deposit accumulation:

1. Deposits accumulate at rates that decrease as the total weight of deposit increases.

2. The change in the rate of deposit accumulation with time may differ with different engine operating conditions.

3. Deposits may change their positions on the spark plug during engine operation under the influences of gravitation and molecular forces and, possibly, forces arising from gas flow within the combustion chamber.

INTRODUCTION

One of the disadvantages of lead as an antiknock agent for aircraft fuel is its characteristic of depositing, either as the metal or as a compound, on combustion-chamber surfaces during engine operation. Lead deposits on spark plugs are known to cause ignition failures both by bridging the electrode gaps and by forming conducting paths across the insulator surfaces and are suspected of lowering the preignition ratings of spark plugs and of contributing to the erosion of spark-plug electrodes. Because of these actions, the deposition of lead on spark plugs not only constitutes a flying hazard but also increases the time and cost of aircraft-engine maintenance, acts as a limiting factor on the use of tetraethyl lead, and constitutes an obstacle to the development of spark plugs of longer service life.

Several investigations of lead fouling in specific engines, notably the V-1710, have been made. Part of the spark-plug fouling difficulty experienced with this type engine has been traced to an uneven distribution of tetraethyl lead to the individual cylinders under cruising conditions; reductions in fouling difficulties have been achieved by the following aids to lead distribution: increase in inlet-air temperature; increase in coolant temperature; and installation of a baffle or a venturi in the main induction trunk. Occasional bursts of high-power operation have been found to reduce deposits accumulated during long periods of cruise operation. NACA tests (reference 1) and tests by the Ethyl Gasoline Corporation have indicated that substantial reductions in lead fouling can be realized by increasing the amount of lead-scavenging agent (ethylene dibromide) in the fuel above the stoichiometric proportion normally used (1-T mix).

At the request of the Air Technical Service Command, Army Air Forces, an investigation of the fundamental processes of lead fouling of spark plugs was begun at the NACA Cleveland laboratory in August 1943. The results reported herein describe the characteristics of the progressive build-up of spark-plug deposits with time during single-cylinder engine tests under nonvarying operating conditions. The results are presented as a general survey of the deposit-accumulation process and of the manner in which the process may be expected to change with widely varying operating conditions. The survey provides a basis for interpreting test results in studies of the effects of specific operating conditions on lead fouling.

METHOD AND APPARATUS

The progressive accumulation of deposit on spark plugs was observed by examining each spark plug and periodically weighing its total deposit throughout a series of test runs at constant engine conditions. Photographic records of the deposits were made in some cases.

Determination of deposit weight. - Deposit weights were determined by weighing the spark plugs on an analytical balance before and after their use in the engine. A cleaning technique was developed to minimize weight errors due to oil, moisture, and other extraneous material on external surfaces. For all of the tests except one, the estimated precision of weight determination (based on weight-precision tests) was ±6 milligrams. For one test the estimated precision was ±10 milligrams but the maximum deviation was only 6 percent owing to the large amounts of deposits accumulated during this test (fig. 1). Tests with nonleaded fuel showed that weight changes caused by carbon fouling and gap erosion were not greater than the uncertainty of weight determination. No oil fouling was observed during the tests. An uncontrollable (but probably small) error occurs in the breaking off of deposit on the periphery of the spark-plug shell when the spark plug is removed from the cylinder.

Test engines. - A CFR F-4 knock-test engine, with slight modifications in the auxiliary equipment, was used for part of the tests. For the remainder of the other tests, a V-1710-51 engine modified for single-cylinder operation was used. The rocker arms, pistons, and connecting rods of the left bank were removed and holes were drilled in five of the right-bank pistons to reduce friction losses. The firing cylinder was 6R. Fuel was injected into a vaporization chamber that was connected to the standard three-port manifold of the engine. The intake ports of cylinders 4R and 5R were blanked. A petcock was installed at the lowest point of each blanked section of the manifold to detect the accumulation of liquid fuel but none was observed. Engine power was absorbed by a dynamometer and standard laboratory equipment was used to measure engine operating conditions.

Spark plugs. - New spark plugs of three different types designated types A, B, and C, were used for the tests.

Fuel. - The fuel used for the tests was AN-F-28, Amendment-2, with tetraethyl-lead additions (1-T mix) in some cases.

RESULTS AND DISCUSSION

Variation of deposition with time. - The history of deposit accumulation on a type A spark plug in the CFR engine is recorded in figure 1. In order that the test might cover the condition of very large total deposit without the necessity for long engine runs, the lead content of the fuel was increased to 34 milliliters per gallon. Qualitatively, the variation of net rate of deposition with time is typical of that observed under a variety of conditions of engine operation, spark-plug type, and lead content of the fuel. The deposit at the end of the test filled the spark-plug-nose cavity approximately to the end of the insulator. A photograph of the spark plug at the end of the test is also shown in figure 1. An attempt to operate the spark plug at high engine power after the completion of the accumulation test was unsuccessful because of short circuiting by the fouling deposit.

Effect of power level. - As shown in figure 2, different engine operating conditions may result in time-accumulation curves of quite different shapes and the relative effects of different operating conditions on total accumulation of deposit may depend upon operating time. The tests were made with the CFR engine, using fuel with a lead content of 4.6 millilitors per gallon, at two different power levels. Spark-plug failure occurred during the low-power run shortly after 14 hours of operation because of the formation of a small ball of lead deposit on an electrode gap. The appearance of the spark plug at this time is shown in figure 3.

Accumulation of deposit masses. - The accumulation of deposit with time in the exhaust spark plug of the converted V-1710 single-cylinder engine is shown in figure 4. The engine was operated at cruise conditions with fuel containing 18 ml TEL per gallon. During the test, the development of deposit on the spark plug was photographically recorded. The photographs, which were taken each time the spark plug was removed from the engine for weighing, are shown in chronological order in figure 5. The spark plug is shown in the same orientation in all photographs, the orientation being approximately that which occurred in the engine. The photographs of figure 5 indicate that a large portion of the deposit existed during engine operation in the form of molten globules, which changed position under the influence of gravitation and molecular forces and, possibly, forces arising from gas flow within the combustion chamber. As the total deposit became large after long operation, the concentration of deposit near the lowest point of the spark-plug cavity became pronounced.

Observations of deposits on many spark plugs at the Cleveland laboratory have shown that the appearances and characteristics of deposits formed under different conditions may be quite different. It is therefore impossible to designate any particular deposit typical; deposits similar to those of figure 5 have, however, been observed on badly fouled spark plugs from engines in service use.

Deposit losses. - The most characteristic feature of the accumulation of lead deposit on spark plugs is the decrease in net rate of deposit with operating time. When the total deposit is large, such a decrease would be expected because of the resultant filling of the spark-plug-nose cavity. Reference 5 has shown that for spark plugs of essentially the same design differing only in the volume of the nose cavity, the rate of accumulation of deposit is a function of the volume of the nose cavity. Filling of the cavity does not, however, explain differences in rates of change of deposition for similar spark plugs such as are illustrated by the curves of figure 2. The only general statement that can be made concerning the accumulation of deposit is that both the initial rate of deposition and its variation with time depend upon the construction of the spark plug and its operating conditions. The manner in which the rate of deposit varies suggests that the net rate is the result of deposition, possibly at a constant rate, and loss of deposit at a rate that increases as the total deposit increases. Two processes of this type might be expected to be independent functions of operating conditions. The nonstationary nature of the deposit, as shown by the photographs of figure 5, suggests that deposit losses might be expected to occur during engine operation. In order to test this possibility, a spark plug was operated in the CFR engine at a specific power of 0.68 indicated horsepower per cubic inch with S reference fuel to which had been added 6 ml TEL per gallon. At the end of $7\frac{1}{2}$ hours, the spark plug had collected 159 milligrams of deposit. The spark plug was then replaced in the engine and operated for 1 hour under the same conditions but with nonleaded S reference fuel. At the end of the hour the deposit weight had fallen to 112 milligrams, a value 30 percent lower than the original deposit weight. A similar test on another spark plug resulted in a deposit loss of 35 percent during the operation with nonleaded fuel. The hypothesis that deposit is continuously being lost during engine operation implies that advantages in antifouling performance can be gained through the use of combustion-chamber and spark-plug constructions that facilitate such losses.

Significance of deposit weights. - The electrical failure of a spark plug by lead fouling occurs when a deposit path of sufficient electrical conductance to prevent sparking is formed between the spark-plug shell or a ground electrode and the center electrode. In the case of direct bridging of the electrode gap (fig. 3), a very small amount of deposit may suffice to cause the actual failure. Experience at the Cleveland laboratory has indicated that gap bridging is not the most common type of failure of spark plugs incorporating large nickel or tungsten electrodes. In the more usual case of failure by conduction along deposits on the insulator, short circuiting does not occur until relatively large quantities of deposit are present. In this case, the occurrence of a short-circuiting path depends upon the amount of deposit present, its distribution, and its electrical conductivity. It seems evident from figure 5 that, aside from certain concentrating influences such as the force of gravity and large temperature differences, the distribution of deposit on the spark-plug surfaces is largely a matter of chance. The amount of deposit and the chemical or physical characteristics of the deposit should then be considered as factors determining the probability of failure, whereas the actual occurrence of failure is dependent upon the distribution of deposit. The rate of accumulation of deposit is a measurable quantity that, when interpreted with due regard for the characteristics of the deposit, is an indication of the probability of failure within a given period of operation. Although the net rate of accumulation is apparently subject to some random variation, as would be expected from the foregoing discussion of the process of deposit build-up, it is a more reproducible quantity than the occurrence of spark-plug failure.

In order to illustrate the variations that may be observed among deposit weights obtained under constant test conditions, the distribution diagram of figure 6 was prepared from the results of 224 deposit-accumulation runs made to date for which deviations from a mean deposit weight could be computed. The diagram of figure 6 includes deviations from the arithmetical mean for all cases in which two or more accumulation runs were made under the same conditions and deviations from the mean-value curves of independent variables. The root-mean-square deviation for the observations of figure 6 is 13 percent. The tests for which the deviations were computed covered a wide range of fuels and engine conditions. Most of the tests were of relatively short duration (about 2 hr). Experience has indicated that percentage deviations from a mean deposit weight for long tests are apt to be as great as those for short tests.

SUMMARY OF RESULTS

Several tests, with constant engine conditions during each test, were made with CFR and V-1710 single-cylinder engines and have shown that the process of accumulation of lead deposits on spark plugs has the following characteristics:

1. Deposits accumulate at rates that decrease as the total weight of deposit increases.

2. The change in the rate of deposit accumulation with time may differ with different engine operating conditions.

3. Deposits may change their positions on the spark plug during engine operation under the influence of gravitation and molecular forces and, possibly, forces arising from gas flow within the combustion chamber.

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1. Mulcahy, B. A., and Zipkin, M. A.: The Effects of an Increase in the Concentration of Ethylene Dibromide in a Leaded Fuel on Lead Deposition, Corrosion of Exhaust Valves, and Knock-Limited Power. NACA ARR No. E5E04a, 1945.

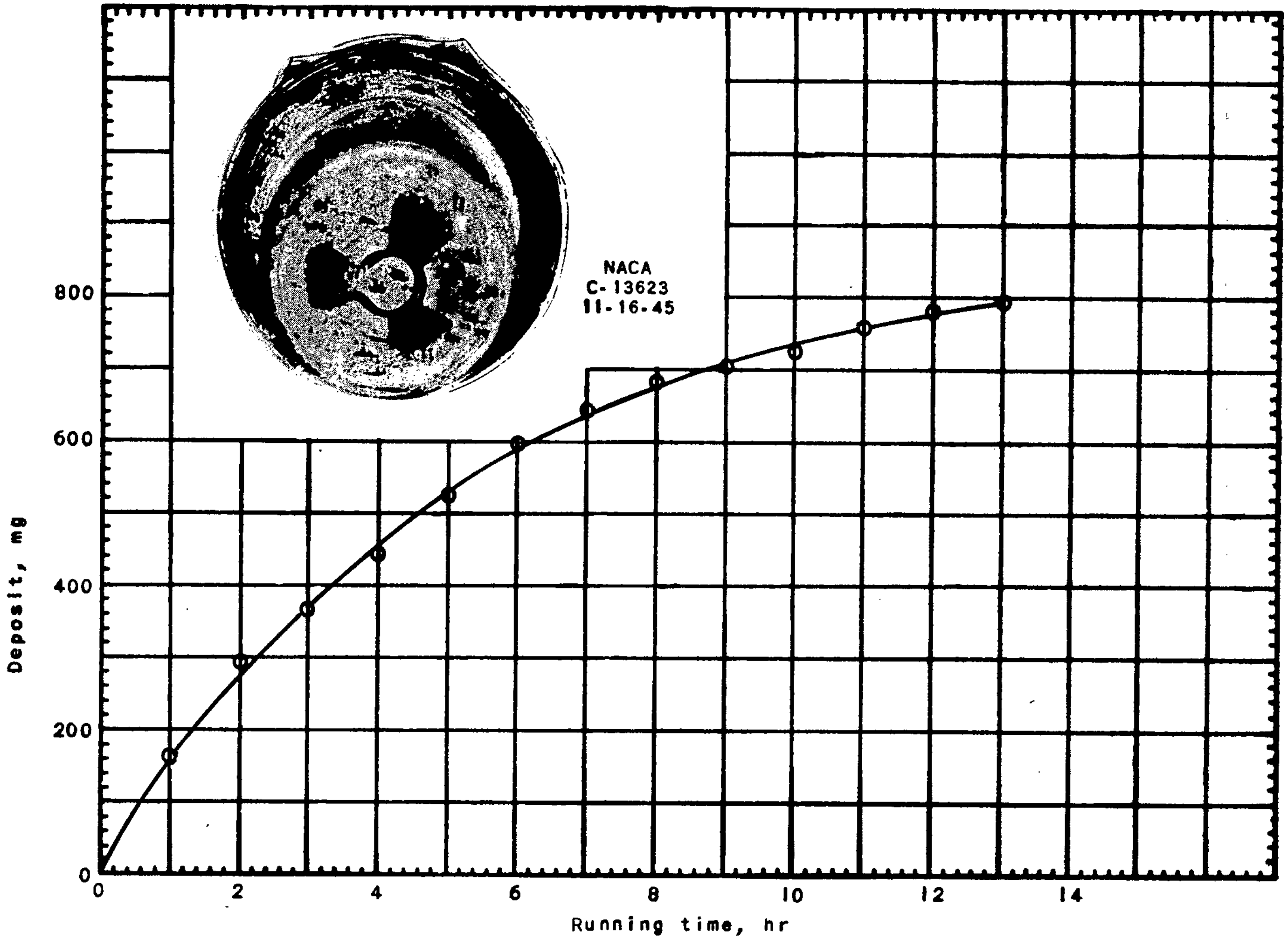

Figure 1. - Accumulation of deposit on a type A spark plug with running time. CFR engine; compression ratio, 6.65; engine speed, 1800 rpm; indicated mean effective pressure, 82 pounds per square inch; fuel-air ratio, 0.10; inlet-air temperature, 85° F; coolant temperature, 212° F; spark advance, 45° B.T.C.; fuel, AN-F-28 with tetraethyl-lead content increased to 34 milliliters per gallon (1-T mix).

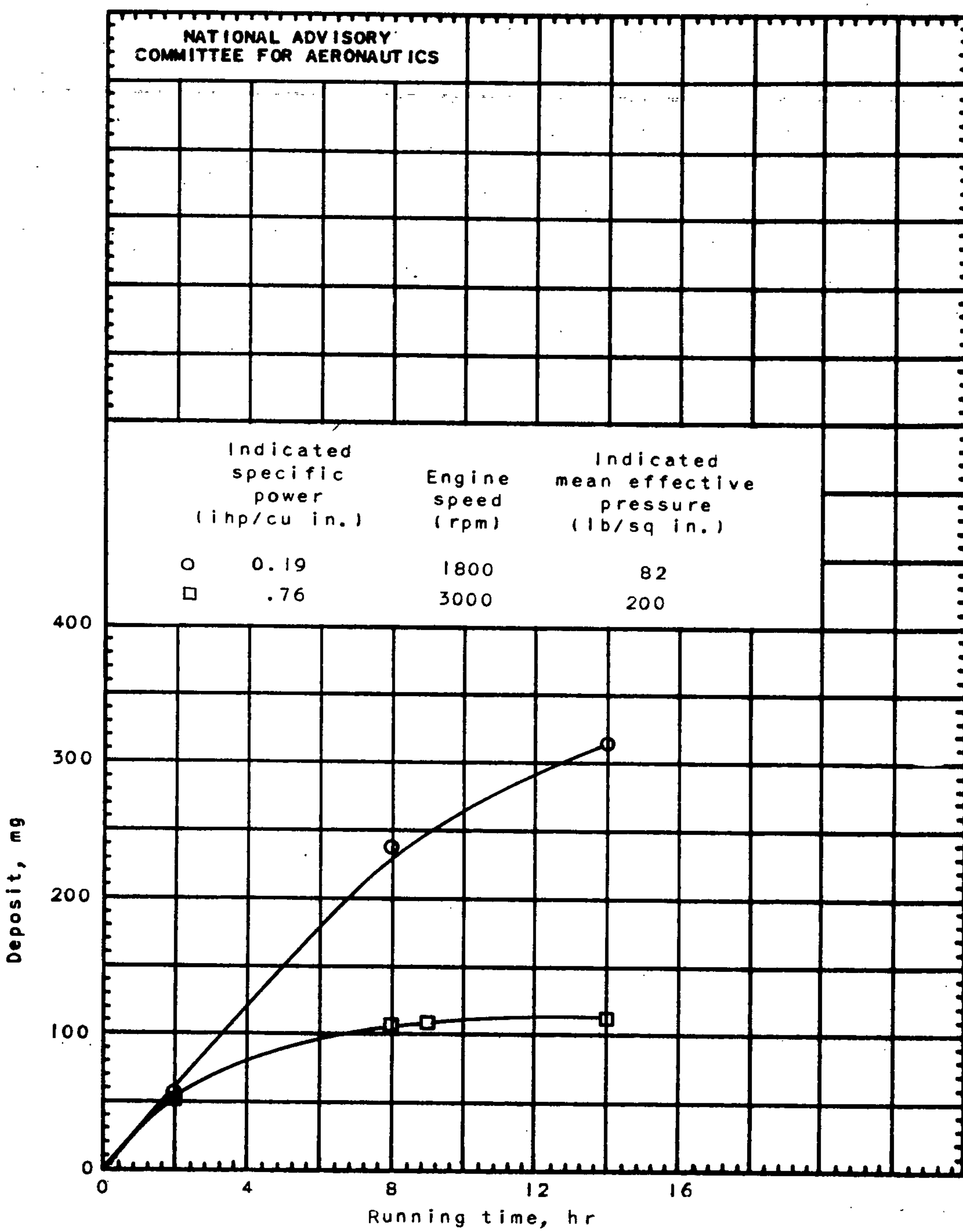

Figure 2. - Effect of power level on deposit accumulation on type C spark plugs with running time. CFR engine; compression ratio, 6.65; fuel-air ratio, 0.10; inlet-air temperature, 90° ± 7° F; coolant temperature, 212° F; spark advance, 45° B.T.C.; fuel, AN-F-28, Amendment 2 (4.6 ml TEL/gal).

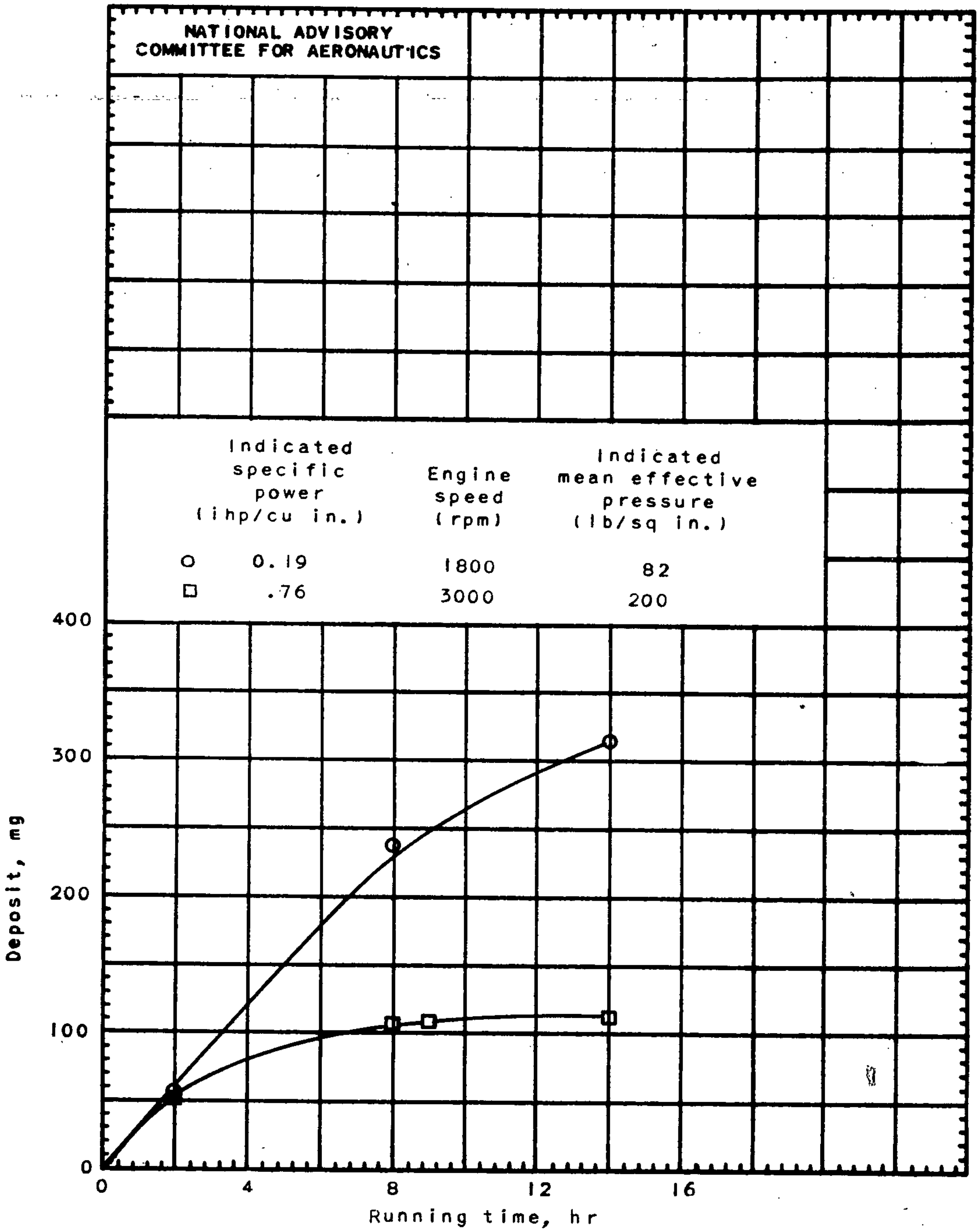

Figure 2. - Effect of power level on deposit accumulation on type C spark plugs with running time. CFR engine; compression ratio, 6.65; fuel-air ratio, 0.10; inlet-air temperature, 90° ± 7° F; coolant temperature, 212° F; spark advance, 45° B.T.C.; fuel, AN-F-28, Amendment 2 (4.6 ml TEL/gal).

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Figure 3. - A type C spark plug with ball in left gap that caused spark-plug failure shortly after 14 hours' operation in CFR engine. Compression ratio, 6.65; engine speed, 1800 rpm; indicated mean effective pressure, 82 pounds per square inch; fuel-air ratio, 0.10; inlet-air temperature, 90° F; coolant temperature, 212° F; fuel, AN-F-28, Amendment-2 (4.6 ml TEL/gal).

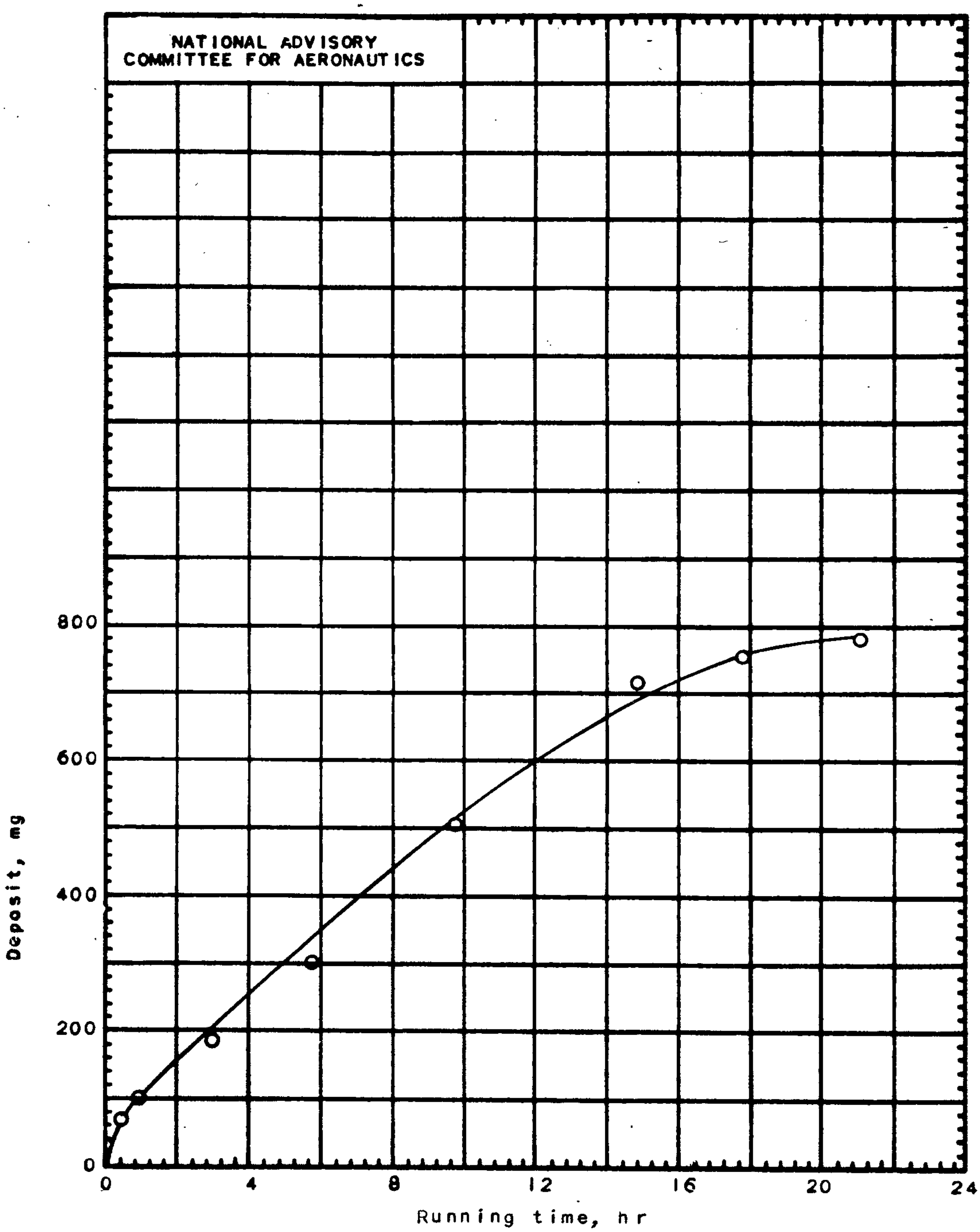

Figure 4. - Accumulation of deposit on a type B spark plug in exhaust position with running time. V-1710 single-cylinder engine; engine speed, 2000 rpm; manifold pressure, 30 inches mercury absolute; fuel-air ratio, 0.10; inlet-air temperature, 85° F; coolant temperature, 250° F; fuel, AN-F-28 with tetraethyl-lead content increased to 18 milliliters per gallon (I-T mix).

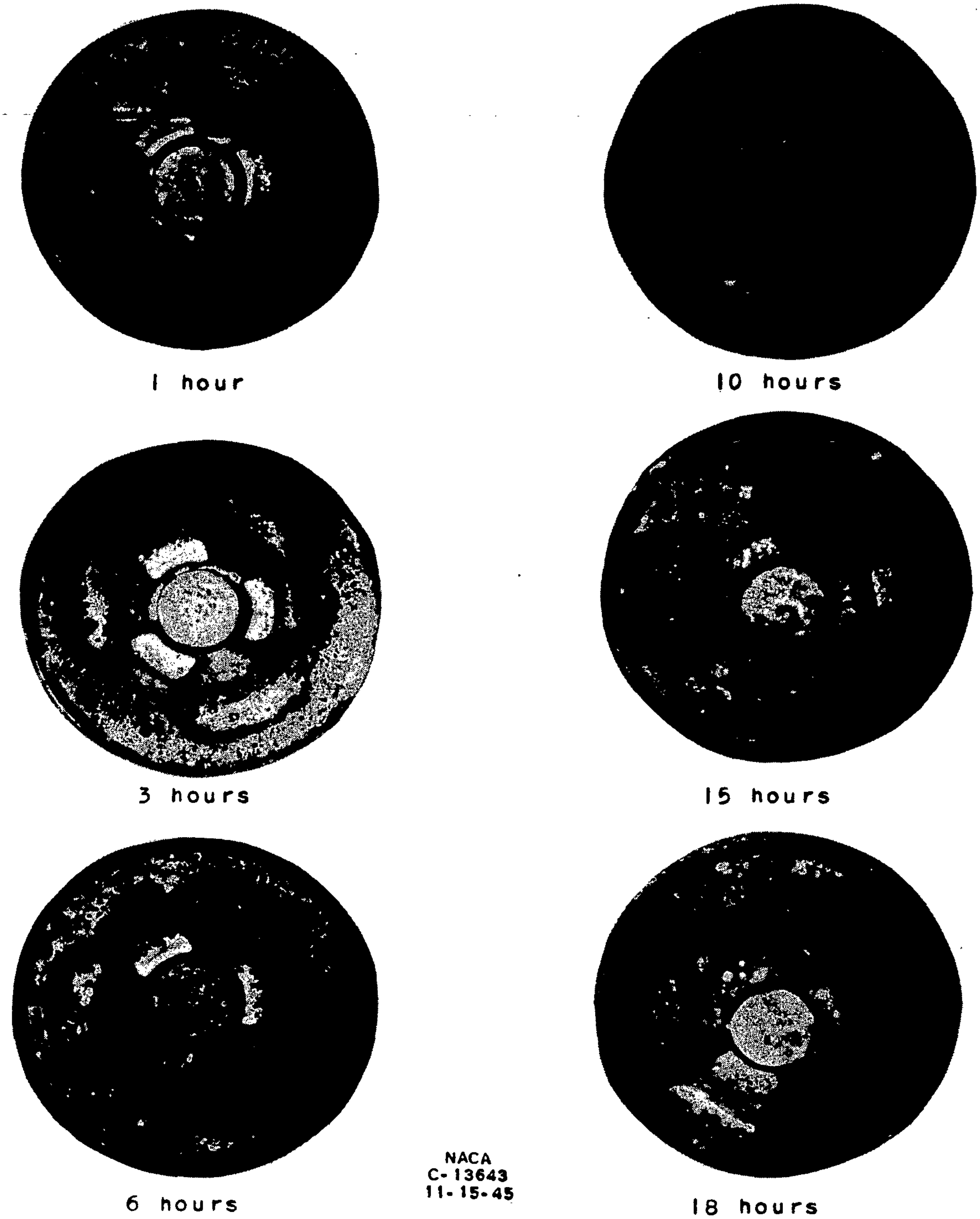

Figure 5. - Accumulation of deposit on a type B spark plug in exhaust position of V-1710 cylinder. Engine speed, 2000 rpm; manifold pressure, 30 inches mercury absolute; fuel-air ratio, 0.10; inlet-air temperature, 85° F; coolant temperature, 250° F; fuel, AN-F-28 with tetraethyl lead content increased to 18 milliliters per gallon (1-T mix).

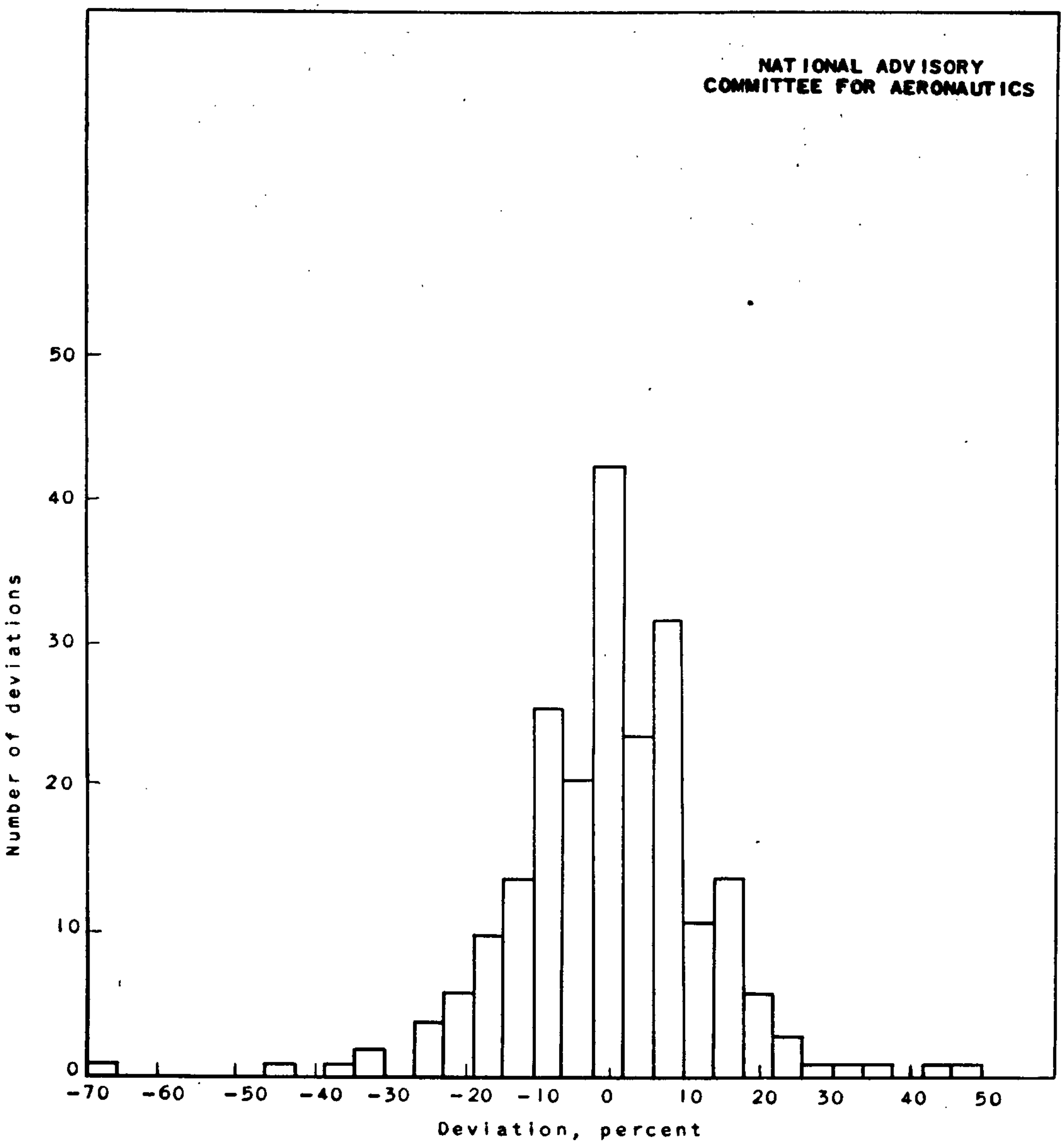

Figure 6. - Distribution diagram showing percentage deviations of individual deposit weights either from a mean of two or more deposit weights obtained under the same conditions or from mean-value curves of independent variables.

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